

# A PRIMORDIAL r-PROCESS?

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## 1 Introduction

A number of possible mechanisms have been suggested to generate density inhomogeneities in the early Universe which could survive until the onset of primordial nucleosynthesis and affect the abundances of the isotopes produced in the big bang [1]. The possibility that the changes in the abundance pattern might be drastic enough to reconcile a closure density of baryons with primordial nucleosynthesis constraints, or to produce a characteristic signature of a phase transition in the early universe has proven exciting enough to inspire a considerable amount of work on inhomogeneous nucleosynthesis. In this work we are not concerned with how the inhomogeneities were generated but we want to focus on the effect of such inhomogeneities on primordial nucleosynthesis. One of the proposed signatures of inhomogeneity, the synthesis of very heavy elements by neutron capture, is analyzed for varying baryon to photon ratios  $\eta$  and length scales  $L$ . A detailed discussion is published in [2]. Preliminary results can be found in [3].

## 2 Method

After weak decoupling the vastly different mean free paths of protons and neutrons create a very proton rich environment in the initially high density regions, whereas the low density regions are almost entirely filled with diffused neutrons. Since the aim of the present investigation was to explore the production of heavy elements, we considered only the neutron rich low density zones. High density, proton rich, environments might produce some intermediate elements via the triple-alpha-reaction, but will in no case be able to produce heavy elements beyond iron. However, we included the effects of the (back) diffusion of neutrons into the proton rich zones. Using a similar approach as introduced in [4, 5], the neutron diffusive loss rate  $\kappa$  is given by

$$\kappa = \frac{4.2 \times 10^4}{(d/a)_{cm\,MeV}} T_9^{5/4} (1 + 0.716 T_9)^{1/2} s^{-1} \quad (1)$$

in the temperature range  $0.2 < T_9 < 1$ . Thus, the only open parameter in the neutron loss due to diffusion is the comoving length scale of inhomogeneities  $(d/a)$ . Small separation lengths between high density zones make the neutron leakage out of the small

low density zones most effective. Large separation lengths make the neutron leakage negligible. (For a detailed derivation of Eq.(1), see also [2]).

Our reaction network consisted of two parts, one part for light and intermediate nuclei, the second part being an r-process code. For light and intermediate nuclei from neutrons and protons to krypton ( $Z=36$ ), from stability to the neutron drip line, we made use of a general nuclear network (of 655 nuclei) which includes neutron, charged particle, and photon induced reaction as well as weak reactions. (For details of the included rates see Appendix B and Tables 1, 2, A1, and A2 in [2]).

The second part was an r-process code that determines the abundances of heavy nuclei. This network extends up to  $Z = 114$  and contains all (6033) nuclei from the so-called valley of beta-stability to the neutron-drip line (see also [6]). The neutron capture rates were calculated with statistical model methods and the beta decay rates were taken from [8], where experimental values were not available (see also [7]). For the calculations in this paper we also introduced (beta delayed) fission of heavy nuclei, as calculated by Thielemann, Metzinger, and Klapdor (1983) [9] with the Howard and Möller (1980) [10] fission barriers and masses (see [7]). These two networks were coupled together such that they both ran simultaneously at each time step, and the number of neutrons produced and captured was transmitted back and forth between them.

### 3 Results and Discussion

The choice of an initial neutron abundance of  $X_n = 1$  (i.e. only neutrons, which is the most favorable condition for the formation of heavy elements) in the low density region leads to a density ratio  $\rho_{\text{low}}/\rho_b = 1/8$  [2]. This leaves as open parameters the baryon to photon ratio  $\eta = n_b/n_\gamma = 10^{-10}\eta_{10}$  and the comoving length scale ( $d/a$ ). Four sets of calculations have been performed, employing  $\eta_{10}$  values of 416, 104, 52, and 10.4. Using the relation [2]

$$\Omega_b h_{50}^2 = 1.54 \times 10^{-2} (T_{\gamma o}/2.78K)^3 \eta_{10} , \quad (2)$$

with the well known present temperature of the microwave background  $T_{\gamma o}$  and the Hubble constant  $H_o = h_{50} \times 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , this corresponds to possible choices of  $(h_{50}, \Omega_b)$  being (2.5,1), (1.3,1), (1,0.8), and (1,0.16). The range covered in  $\eta_{10}$  extends from roughly a factor of 2.2 below the lower limit to a factor of 13 above the upper limit for  $\eta$  in the standard big bang. For each of the  $\eta$ -values we considered four different cases of  $d/a$ : (0)  $\infty$ , resulting in negligible neutron back diffusion, (1)  $10^{7.5} \text{ cm MeV}$ , (2)  $10^{6.5} \text{ cm MeV}$ , and (3)  $10^{5.5} \text{ cm MeV}$ . (This corresponds to distances between nucleation sites of  $\infty$ , 2700, 270, and 27 m, respectively, at the time of the quark-hadron phase transition). The resulting abundances for heavy elements are shown in Tab. 1. One notices the exponential increase in r-process abundances with increasing  $\eta$ . This is due to “fission cycling”, whereby each of the fission fragments can capture neutrons and finally form again heavy nuclei, which are also prone to fission [11]. This is of particular importance in environments with a long duration of high neutron densities, and was therefore suggested as relevant to primordial nucleosynthesis in neutron rich zones of an inhomogeneous big bang [4]. In contrast to the operation of the r-process in explosive

stellar environments, confined to a few seconds, this process in the neutron rich regions associated with an inhomogeneous big bang is only limited by the neutron half-life and can go on for an extended period of time. One of the remarkable features of an r-process with fission cycling is that the production of heavy nuclei is not limited to the r-process flow (neutron captures and beta-decays) coming from light nuclei, but requires only a small amount of fissionable nuclei to be produced initially. The total mass fraction of heavy nuclei is doubled with each fission cycle and can thus be written as  $X_r = 2^n X_{seed}$ . Here,  $n$  is the number of fission cycles and  $X_{seed}$  denotes the initial mass fraction of heavy nuclei. The effectiveness of fission cycling can be seen in Fig. 1. The main parameter that determines the number of fission cycles is the rate of the r-process flux, which is a function of the location of the r-process path with respect to the stability line, and thus dictates the typical beta decay half lives. The location of the r-process path is a function of the neutron number density  $n_n$  and temperature  $T$ , coming closer to stability for decreasing  $n_n$  or increasing  $T$ , thus increasing cycle times and decreasing the number of cycles which in turn leads to smaller abundance predictions.

Since the formation of heavy elements beyond Fe and Kr is a very sensitive measure of  $\eta$ , it can be used to provide an independent upper limit for the product  $\Omega_b H_0^2$ . Fig. 2 shows observational (upper) limits to the primordial creation of heavy [7, 12, 13] and light [14, 15, 16, 17] element abundances to our results. The tightest constraints are given by the light elements including Li, Be, and B (see however recent doubts on the primordial  ${}^7\text{Li}$  abundance [18]) for which the conditions cannot differ much from the standard big bang.

How do changes in the reaction rates leading to heavy elements affect our results? Some test calculations were performed with a variation of the  ${}^8\text{Li}(\alpha, n){}^{11}\text{B}$  rate, one of the two bottle necks toward heavy nuclei (the other one being  ${}^{14}\text{C}(\alpha, \gamma){}^{18}\text{O}$ ). Recent experiments [19] seem to suggest that the rate used in our calculations [20] has to be increased by a factor of 3. It was found that such a change enters only linearly in the resulting heavy element abundances. This can be understood easily, as the seed production of heavy elements varies linearly with the Li-rate, and even for strong fission cycling this behavior is not changed because  $X_{heavy} = X_{seed} \times 2^n$ . A similar effect was found for the  ${}^{18}\text{O}(n, \gamma){}^{19}\text{O}$  rate which was changed by a factor of 10 in a recent investigation [21]. Thus, the total change in heavy element abundances is a factor of 30. This is also shown in Fig. 2. (However, note that these changes are not included in the values given in Tab. 1).

Provided that density fluctuations exist with large scale lengths in comparison to the neutron diffusion length, the corresponding limits for  $\eta_{10}$  or  $\Omega_b h_{50}^2$  change to 104 and 1.6, respectively, at which heavy element abundances are produced in inhomogeneous big bang models at a level comparable to the ones seen at lowest observable metallicities. This reduces the difference between the constraints from light and heavy elements, although the light element constraint is still tighter. It also underlines that not all reactions of importance are fully explored, yet, and future changes can be expected.

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$\eta_{10}$	$\Omega_b h_{50}^2$	$d/a$	>Kr
416	6.4	0	$0.170 \times 10^{-02}$
		1	$0.133 \times 10^{-04}$
		2	$0.190 \times 10^{-13}$
		3	—
104	1.6	0	$0.227 \times 10^{-11}$
		1	$0.735 \times 10^{-13}$
		2	—
		3	—
52	0.8	0	$0.628 \times 10^{-15}$
		1	$0.253 \times 10^{-16}$
		2	—
		3	—
10.4	0.16	0	—
		1	—
		2	—
		3	—

Table 1: Mass fractions of heavy nuclei (see text).

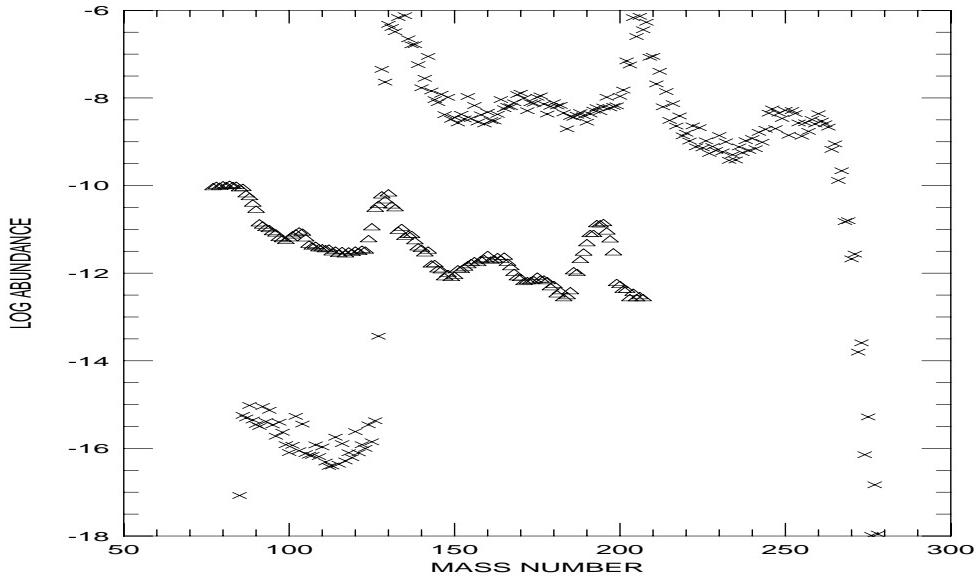


Figure 1: r-process abundances for  $\eta_{10} = 416$  and no diffusion (crosses) compared to the solar abundance (triangles). Fission cycling has enhanced the initial “seed” amount of heavy elements by 8 orders of magnitude. (The shift of the abundance peaks is due to the low neutron densities at late time [2,3]).

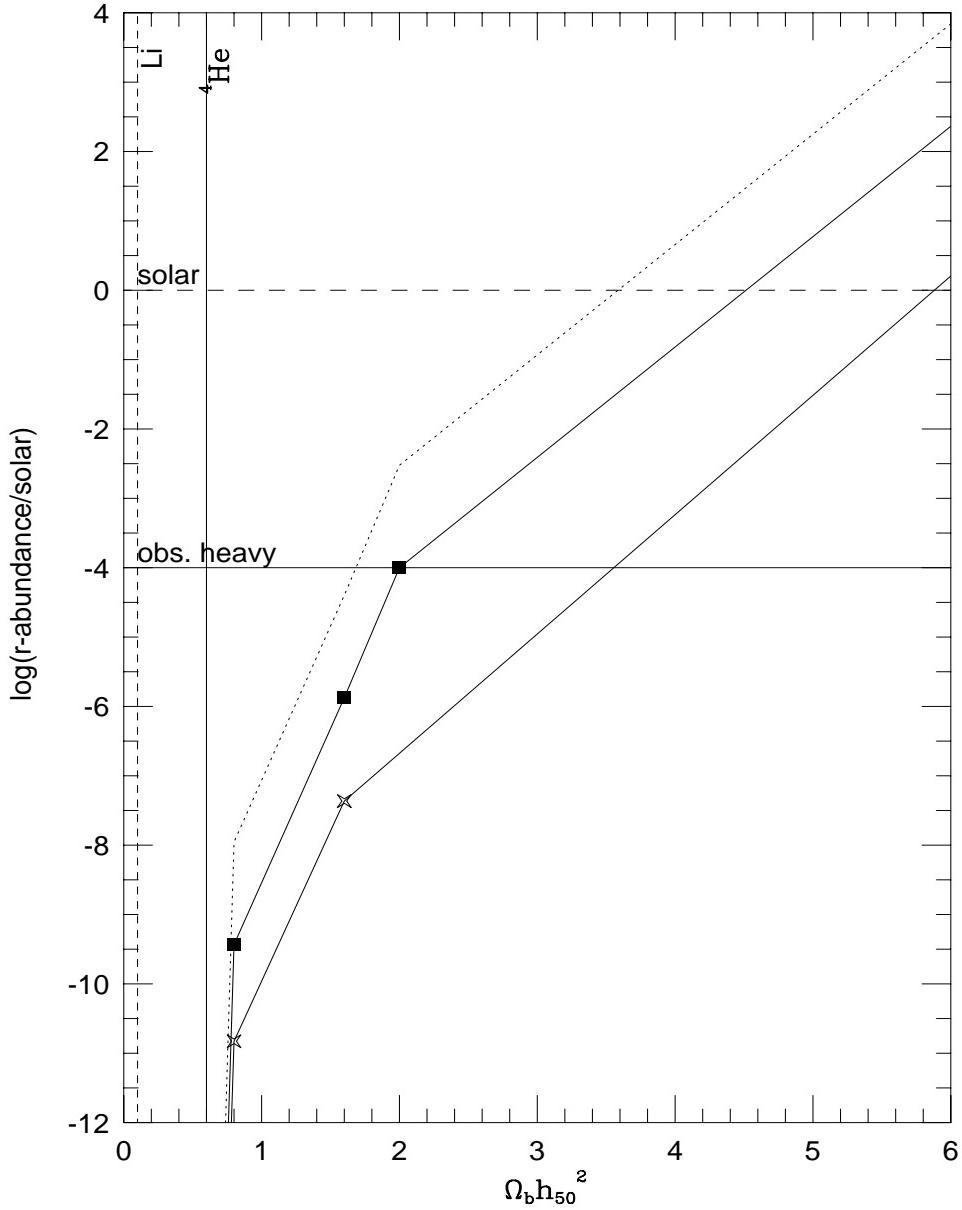


Figure 2: Limits on  $\Omega_b h_{50}^2$  from light and heavy element abundances. Abundances are normalized to solar. Shown are the results for different length scales of inhomogeneities, i.e. case 0 (full sq.), 1 (crosses), and 2 (open sq.). (The lines are merely drawn to guide the eye). Also shown is the result for the enhanced rates (dotted line). The horizontal solid line gives the observational upper limit for primordial heavy abundances. The limits on  $\Omega_b h_{50}^2$  resulting from the calculated values for the light element abundances are given by the vertical full and dashed lines. (See text).

## References

- [1] R.A. Malaney and G.J. Mathews, *Phys. Rep.* **229** (1993) 145.
- [2] T. Rauscher, J.H. Applegate, J.J. Cowan, F.-K. Thielemann, and M. Wiescher, *Ap.J.*, in print.
- [3] F.-K. Thielemann, J.H. Applegate, J.J. Cowan, and M. Wiescher, in *Nuclei in the Cosmos*, ed. H. Oberhummer (Springer 1991), p.147.
- [4] J.H. Applegate, *Phys. Rep.* **163** (1988) 141.
- [5] J.H. Applegate, C.J. Hogan, and R.J. Scherrer, *Ap. J.* **329** (1988) 572.
- [6] J.J. Cowan, A.G.W. Cameron, and J.W. Truran, *Ap. J.* **265** (1983) 429.
- [7] J.J. Cowan, F.-K. Thielemann, and J.W. Truran, *Phys. Rep.* **208** (1991) 267.
- [8] H.V. Klapdor, J. Metzinger, and T. Oda, *At. Data Nucl. Data Tables* **31** (1984) 81.
- [9] F.-K. Thielemann, J. Metzinger, and H.V. Klapdor, *Z. Phys. A* **309** (1983) 301.
- [10] W.M. Howard and P. Möller, *At. Data Nucl. Data Tables* **25** (1980) 219.
- [11] P.A. Seeger, W.A. Fowler, and D.D. Clayton, *Ap. J. Suppl.* **97** (1965) 121.
- [12] T. Beers, G.W. Preston, and S.A. Shectman, *Astron. J.* **103** (1992) 1987.
- [13] G.J. Mathews, G. Bazan, and J.J. Cowan, *Ap. J.* **391** (1992) 719.
- [14] B.S. Meyer, C.R. Alcock, G.J. Mathews, and G.M. Fuller, *Phys. Rev. D* **43** (1991) 1079.
- [15] H. Kurki-Suonio, R.A. Matzner, K.A. Olive, and D.N. Schramm, *Ap. J.* **353** (1990) 406.
- [16] S.G. Ryan, J.E. Norris, M.S. Bessel, and C.P. Deliyannis, *Ap. J.* **388** (1992) 184.
- [17] D.K. Duncan, D.L. Lambert, and D. Lemke, *Ap. J.*, in print.
- [18] C.P. Deliyannis, M.H. Pinsonneault, and D.K. Duncan, *Ap. J.* **414** (1993) 740.
- [19] Z.Q. Mao, R.B. Vogelaar, A.E. Champagne, J.C. Blackmon, R.K. Das, K.I. Hahn, and J. Yuan, *Nucl. Phys.* **A567** (1994) 125.
- [20] T. Rauscher, K. Grün, H. Krauss, H. Oberhummer, and E. Kwasniewicz, *Phys. Rev. C* **45** (1992) 1996.
- [21] H. Beer, F. Käppeler, and M. Wiescher, in *Capture Gamma-Ray Spectroscopy*, ed. J. Kern (Bristol: IOP), in print.